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RELATIONSHIP AMONG TORNADOES, VORTICITY ACCELERATION, AND AIR MASS STABILITY

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ABSTRACT

Numerical computations of the local change with respect to time of the local tendency of the vertical component of the vorticity of the surface wind and a stability index were made at 3-hour intervals for fifteen tornado days during the period from February to June 1961. Average values of these two parameters were computed with reference to tornado occurrences at the center of the computation grid. These average values are shown for five time periods: 9 to 12 hr., 6 to 9 hr., 3 to 6 hr., 0 to 3 hr. prior to tornado occurrences, and 0 to 3 hr. after tornado occurrences. It appears the tornadoes develop within an area under the influence of increasing cyclonic vorticity tendency and characterized by a conditionally unstable air mass. These conditions apparently exist during a short time interval before tornado occurrence, with tornadoes developing only after their combined intensity reaches a critical value.

1. INTRODUCTION

Successful tornado prediction in the past has resulted largely from forecasters' ability to evaluate the potential thermal instability of the air mass, coupled with their ability to estimate correctly the strength of the synoptic system containing the tornado development. Tornadoes develop, from the one extreme, in weak motion systems with strong air mass instability, to the other extreme, in strong motion systems with weak air mass instability. The search for the proper combination of these conditions prior to tornado development has been difficult, partly because of the lack of an objective method of evaluating the intensity of the motion system. The purpose of this paper is to describe an objective machine method for evaluating air mass stability and the intensity of the motion system on a space and time scale geared to the operational requirements of the Severe Local Storms Forecast Center. In this objective method the air mass stability is based on the difference between the 500-mb. temperature and the temperature of a parcel of air lifted moist adiabatically from its sea level wet bulb temperature to 500 mb. The strength of the motion system is based on the local change of the vorticity tendency at the surface. Development and testing of this objective machine method was done on the IBM 1620 Data Processing System in the Severe Local Storms Forecast Center.

2. SOURCE DATA

Data for the project consisted of sea level pressure, surface temperature, dew point, wind direction, and wind speed for 115 weather stations in the Central and Southern Plains of the United States. Reports were assembled for the 6-hourly and 3-hourly reporting times. Dates included were February 17, March 5, 26, April 30, May 3, 4, 5, 6, 7, and June 3, 4, 5, 6, 7, 8, 1961. Tornadoes occurred, either isolated or in groups, on all of these days in the area under study. Temperature and dew point were reduced to sea level using standard lapse rates of 5.37667 and 0.91403°F./1000 ft., respectively. Surface winds were broken down into u and v components and data interpolated to points on a grid of 20 rows by 21 columns. Grid points were approximately 43 n. mi. apart. The grid was centered near central Oklahoma, extended westward to the Rockies, eastward to the Mississippi, southward to southern Texas, and northward to central Nebraska and southern Iowa. Data interpolation was done by finding the closest three stations that enclosed a grid point in a triangle and interpolating linearly to the point.

3. VORTICITY ACCELERATION

In an earlier study, Foster [1] found that tornadoes occurred in the eastern portions of maxima of cyclonic vorticity, cyclonic vorticity tendency, negative divergence, and negative divergence tendency. Although there was a very large area of instability, tornadoes occurred only in the area where the above mentioned maxima traversed the unstable area. In this study the strength of the motion system has been based on the local change with respect to time of the vorticity tendency at the surface of the earth. Since the vorticity tendency is the rate of production of vorticity, another time derivative of the vorticity tendency indicates a quickening or a retardation of this process and, in this sense, can be called vorticity acceleration. The vorticity acceleration equation, as presented by House [2] is as follows:

$$\frac{\partial^2\zeta}{\partial t^2}=-\frac{\partial}{\partial t}[\mathbf{V}\cdot\nabla(\zeta+f)]-\mathrm{div}_2\mathbf{V}\frac{\partial}{\partial t}(\zeta+f)-(\zeta+f)\frac{\partial}{\partial t}(\mathrm{div}_2\,\mathbf{V}) \tag{1}$$

It can be seen that all of the terms mentioned in Foster's first study appear in this equation with the proper sign so as to contribute to cyclonic vorticity acceleration. The term that involves the local change of the advection of vorticity would contribute to cyclonic vorticity acceleration in the forward, or downwind, portions of the vorticity maximum, if the vorticity gradient was increasing and/or the wind was increasing locally with respect to time. House goes on to explain that most of the successful rules for tornado prediction can be relegated to their proper positions through an evaluation of equation (1).

The vorticity acceleration equation used here is in a slightly different form than that presented by House. It can be shown by two partial differentiations of the equation for the vertical component of the absolute vorticity with respect to time at the surface where vertical velocity is zero, that

$$\frac{\partial^2\zeta}{\partial t^2}=\frac{\partial}{\partial x}\left[-f\frac{\partial u}{\partial t}+f\frac{\partial u_g}{\partial t}-u\frac{\partial}{\partial x}\left(\frac{\partial v}{\partial t}\right)\right.$$
$$\left.-\frac{\partial u}{\partial t}\frac{\partial v}{\partial x}-v\frac{\partial}{\partial y}\left(\frac{\partial v}{\partial t}\right)-\frac{\partial v}{\partial t}\frac{\partial v}{\partial y}\right]-\frac{\partial}{\partial y}\left[f\frac{\partial v}{\partial t}-f\frac{\partial v_g}{\partial t}\right.$$
$$\left.-u\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial t}\right)-\frac{\partial u}{\partial t}\frac{\partial u}{\partial x}-v\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial t}\right)-\frac{\partial v}{\partial t}\frac{\partial u}{\partial y}\right]$$

where

$$\frac{\partial u}{\partial t}=f(v-v_g)-u\frac{\partial u}{\partial x}-v\frac{\partial u}{\partial y},\qquad \frac{\partial v}{\partial t}=-f(u-u_g)-u\frac{\partial v}{\partial x}-v\frac{\partial v}{\partial y}$$

and

$$u_g=-\frac{RT}{fp}\frac{\partial p}{\partial y},\qquad v_g=\frac{RT}{fp}\frac{\partial p}{\partial x}$$

The symbols used have their usual meaning. Two terms,

$$\frac{\partial}{\partial x}\left(f\frac{\partial u_g}{\partial t}\right)+\frac{\partial}{\partial y}\left(f\frac{\partial v_g}{\partial t}\right)$$

are omitted from the equation. Evaluating these terms by finite differences with Δx and Δy of 86 n. mi. yields maximum values normally one to two orders of magnitude less than total values for all of the terms. All of the other terms were evaluated.

4. STABILITY INDEX

The significance of the stability index relative to tornado development is discussed in [3] and the accompanying references. Usually, a stability index is found by lifting a parcel of air from 850 mb., or from the top of a moist layer, to 500 mb. and finding the difference between the lifted parcel temperature and the 500-mb. temperature. Often a parcel whose temperature and mixing ratio are means for the lower 100-mb. layer, or for the lower 3,000 ft., is lifted to 500 mb. to find the lifted parcel temperature. In this study, the parcel is lifted from the surface to 500 mb. to find a lifted parcel temperature. The advantage of using a surface parcel is the increased frequency of surface observations over upper-air soundings and the closer network of surface reports compared to upper-air soundings. Actually, the surface temperature and dew point are reduced to sea level along standard lapse rates mentioned earlier; the lifted parcel temperature at 500 mb. along the pseudoadiabat that passes through the sea level wet bulb temperature, is subtracted from the observed 500-mb. temperature to find the stability index. The sea level wet bulb temperature was computed from an equation used by the Weather Records Processing Center formerly located at Kansas City.

$$T_w=T-ab$$

$$a=.034n-.00072\,n(n-1)$$

$$n=(T-T_d)/10$$

$$b=T+T_d-2p_s+108$$

T, T_w, T_d are sea level temperature, wet bulb temperature, and dew point temperature, respectively, in °F. and p_s is sea level pressure in inches of Hg.

The relationship between sea level wet bulb temperature and the corresponding 500-mb. temperature on a pseudo-adiabat through the sea level wet bulb temperature was obtained by selecting pairs of data from tables given in [4] and fitting the following polynomial, accurate to within ± 0.18°C.

$$T_5=-45.682668+1.905894\,T_s-0.00560553\,T_s^2$$

T_5 is the lifted temperature at 500 mb. and T_s is the wet bulb temperature at sea level, both in °C. Since 500-mb. temperatures are available only at 0000 and 1200 GMT, and computations were made every 3 hr., something should be said about the treatment of 500-mb. temperatures at the intervening hours. The primary area of interest for possible tornado activity lies within the warm sector of cyclones where adiabatic cooling at 500 mb. from vertical motion is generally opposed by warm air advection. Therefore, the temperature was held constant for a few trial cases until it became obvious that there was too much change between 0900 and 1200 GMT, and between 2100 and 0000 GMT. In order to smooth these changes a diurnal correction for the 500-mb. temperature was introduced. It varied by months and time of day as given in table 1. When these corrections were added to the 500-mb. temperatures, the stability patterns showed smoother continuity from one time period to the next without the obvious break in continuity just prior to new 500-mb. temperature observations.

5. RESULTS OF COMPUTATIONS

Results of these computations have been averaged to show their relationship to a large number of tornadoes. Tornadoes were plotted and given the coordinates of the grid point closest to which they occurred. The grid was then centered on the coordinates of each tornado and the point values at each grid point five rows and five columns in all directions from the tornado were averaged. The averaging process was repeated five times, for data 9 to 12 hr., 6 to 9 hr., 3 to 6 hr., 0 to 3 hr. prior to, and 0 to 3 hr. after tornado occurrences. Figure 1 shows a positive vorticity acceleration area entering the western side of the computation area and beginning to intersect an unstable tongue of air extending northward from the southern edge of the computation area, 9 to 12 hr. before 86 tornadoes occurred at the center of the computation area. It is interesting to note the combined values of stability index and vorticity acceleration. It is convenient to combine the two values by multiplying the vorticity acceleration value by 100, changing the sign of the stability index, and adding the two fields graphically. The combined value of the two parameters for the 9 to 12-hr. computation has a maximum of 5.3 at four grid points (about 172 mi.) west of tornado occurrence.

Figure 2 shows the relationship 6 to 9 hr. prior to 93 tornado occurrences. The vorticity acceleration area has increased slightly and moved closer to the tornado location.

TABLE 1.—*Diurnal corrections (° C.) of 500-mb. temperature*

Time (GMT):	00	03	06	09	12	15	18	21
February	0.0	−0.2	−0.4	−0.6	0.0	+0.2	+0.4	+0.6
March	0.0	−0.3	−0.6	−0.9	0.0	+0.3	+0.6	+0.9
April	0.0	−0.4	−0.8	−1.2	0.0	+0.4	+0.8	+1.2
May	0.0	−0.5	−1.0	−1.5	0.0	+0.5	+1.0	+1.5
June	0.0	−0.6	−1.2	−1.8	0.0	+0.6	+1.2	+1.8

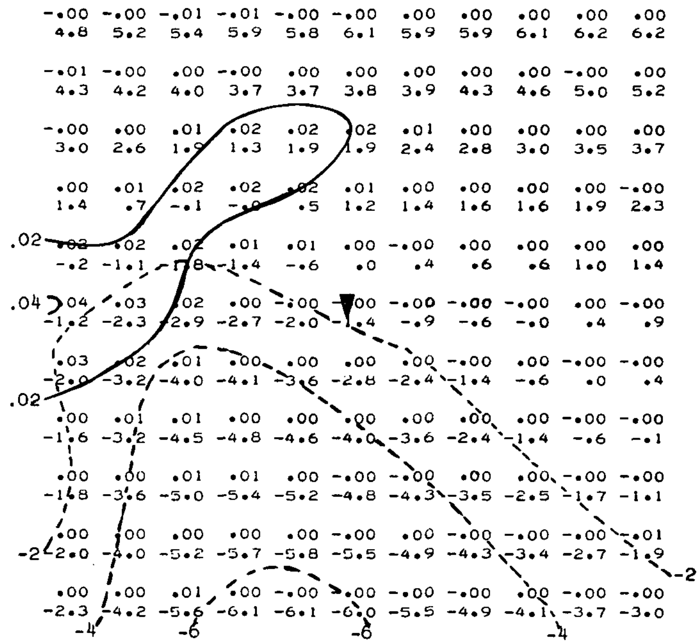

FIGURE 1.—Average vorticity acceleration (solid lines) in units of hr.$^{-3}$, and average stability index (broken lines) in °C., 9 to 12 hr. prior to 86 tornadoes.

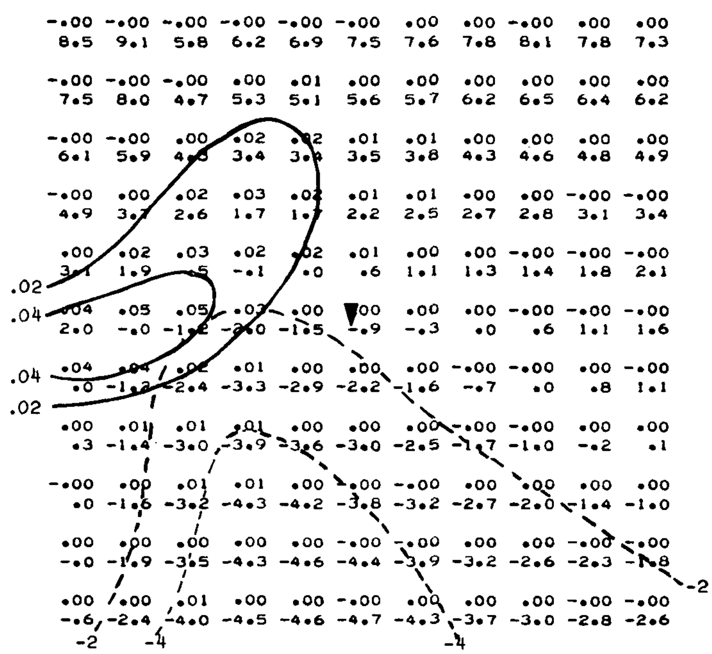

FIGURE 2.—Average vorticity acceleration (solid lines) in units of hr.$^{-3}$, and average stability index (broken lines) in °C., 6 to 9 hr. prior to 93 tornadoes.

The northern portion of the unstable tongue of air has shifted eastward slightly with little change in intensity. The combined value of the two parameters is 6.2 at three grid points (about 129 mi.) west of tornado location, having increased and moved closer.

Figure 3 shows average values 3 to 6 hr. prior to 93 tornado occurrences. The maximum combined value is

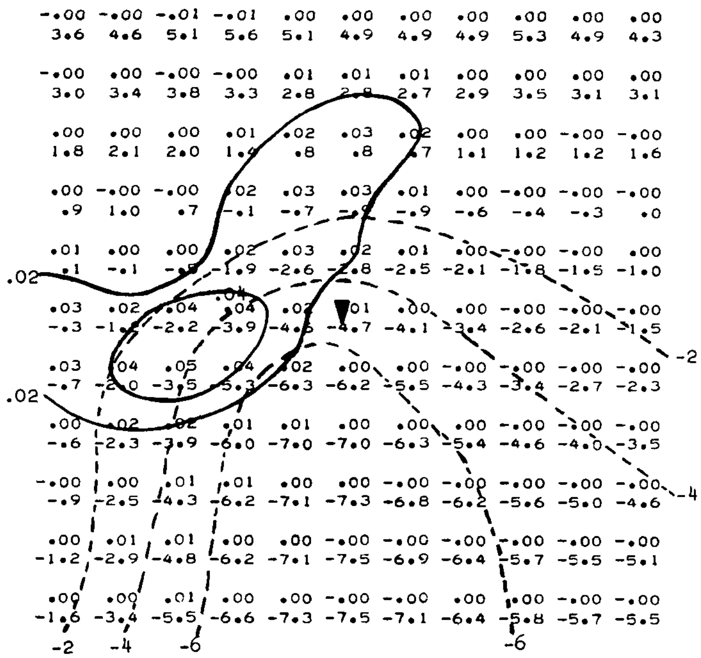

FIGURE 3.—Average vorticity acceleration (solid lines) in units of hr.$^{-3}$, and average stability index (broken lines) in °C., 3 to to 6 hr. prior to 93 tornadoes.

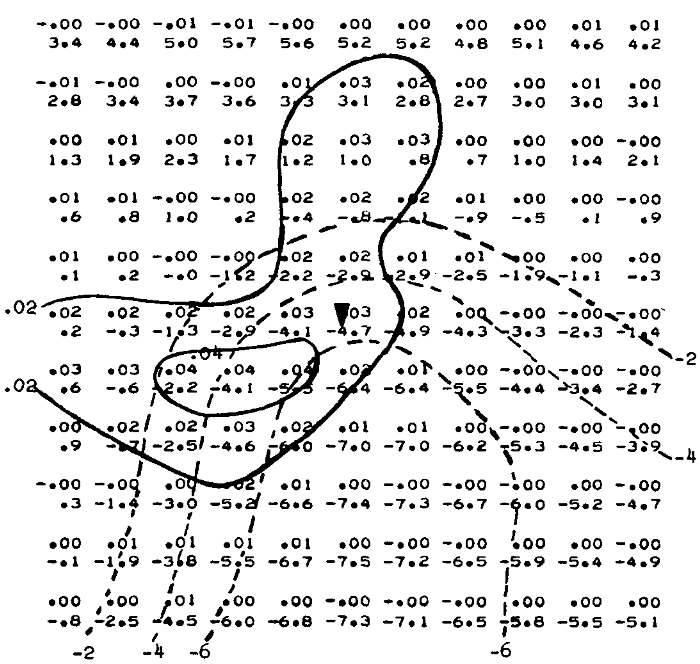

FIGURE 4.—Average vorticity acceleration (solid lines) in units of hr.$^{-3}$, and average stability index (broken lines) in °C., 0 to 3 hr. prior to 93 tornadoes.

9.3 at two grid points west and one south (about 96 mi. west-southwest) of tornado occurrence, having increased again and moved still closer.

Figure 4 shows average values 0 to 3 hr. prior to 93 tornado occurrences. The maximum combined value is 9.5 at one grid point west and one south (about 61 mi. southwest) of tornado occurrence, having increased even more and moved very close to tornado location. Combined values probably exceed 10 where isolines of 0.04 and −6 intersect. The thousandths position of the vorticity acceleration computation is dropped and the hundredths position is not rounded off to the nearest one one-hundredth.

4.2 11.6		3.9 5.5
	7.7 5.6	
9.5 6.0		7.4 3.8

FIGURE 5.—Sum of average values of vorticity acceleration (10^{-2} hr.$^{-3}$), plus stability index (sign reversed), top number, and standard deviation, bottom number, 0 to 3 hr. prior to 93 tornadoes near the center point.

Figure 5 shows combined values with their standard deviations at tornado location and at four surrounding grid points. The combined value southeast of tornado location is the most stable. One can imagine the air mass being the least disturbed at this point by transient mesoscale systems associated with tornado development. The point northwest of tornado location is the most unstable. Here one would expect the air mass frequently to be disturbed by mesoscale systems. The points between have occasionally been disturbed by mesoscale systems between observation time and tornado time, which may have been as much as 3 hr.

Figure 6 shows average values 0 to 3 hr. after 92 tornado occurrences. The air mass has stabilized at the point of tornado occurrence and the positive vorticity acceleration area has split and moved away from the tornado location. The combined value of the parameters, 9.2, two grid points to the south of tornado location indicates tornadoes may have developed in this area at a later time. On occasion they did, but more frequently the trend of the increase of the combined value of the parameters reversed at this point and by 3 to 6 hr. after tornado occurrence the two patterns of vorticity acceleration and stability index had pulled away from each other.

The sequence of patterns discussed above suggests strongly that tornadoes occur within an area under the influence of positive vorticity acceleration characterized by a conditionally unstable air mass. The combined value of the two parameters reaches a critical value at tornado occurrence that may be very close to 10.

6. TESTING THE COMBINED VALUE

The combined value of 10 discussed in the previous section was tested on all tornadoes occurring within the computation area. It was discovered that often the vorticity acceleration value alone exceeded 0.10, and occasionally the stability index was less than −10, yet no tornadoes occurred. Generally, the stability index was

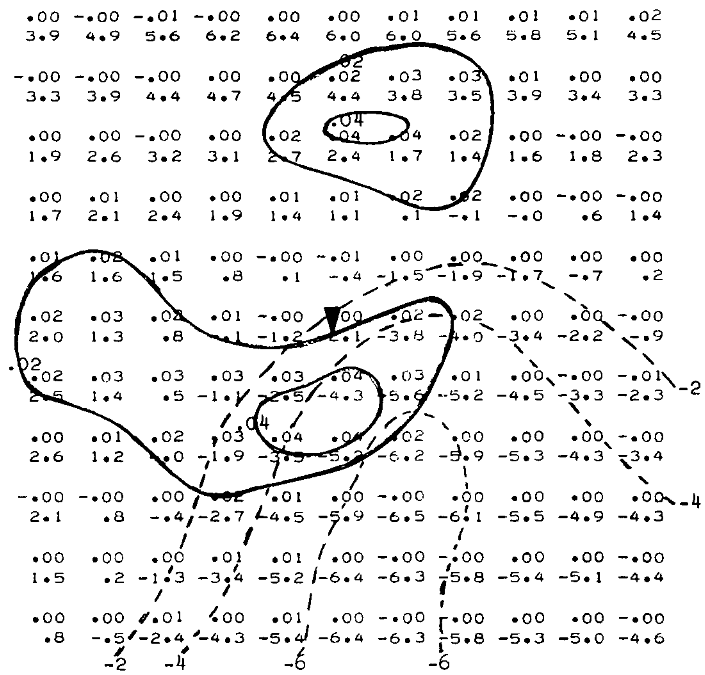

FIGURE 6.—Average vorticity acceleration (solid lines) in units of hr.$^{-3}$, and average stability index (broken lines) in °C., 0 to 3 hr. after 92 tornadoes.

—2 or less, the vorticity acceleration 0.02 or larger, and their combined value 10 or larger for tornadoes to occur. These values were tested on the data 0 to 3 hr. prior to tornado occurrences. There were 40,014 grid point computations made, of which 1,070 had combined values of 10 or more. Of these, 423 were associated with tornadoes either at the grid point or within one grid point from the compact pattern made by the equal to or greater than 10 values. The remaining 647 had no tornadoes reported in the vicinity. These points were concentrated in two general synoptic areas. One area was in the wake depression that frequently develops to the rear of instability lines where the vorticity acceleration shows a positive value, but, according to Williams [5], the air mass has not recovered from the subsidence that followed the main thunderstorm complex. The other area was in the warm moist unstable tongue of air farther to the south of tornado development. This is a region where, according to [3], the moist layer which initially is of more or less uniform depth, decreases in depth or remains unchanged, capped securely by a temperature inversion.

TABLE 2.—*Relationships between tornado occurrence and combined value of vorticity acceleration and stability index*

	Totals	Percent
Number of points evaluated	40,014	100
Number with values <10	38,944	97
Number with values ≥10	1,070	3
Number with values ≥10	1,070	100
Associated with tornadoes	423	40
Not associated with tornadoes	647	60
Number of tornadoes reported	185	100
Number of tornadoes at or within one grid point of a value ≥10	142	77
Number of tornadoes with values <10	43	23

Another test considered the tornadoes reported. Of the 185 tornadoes reported, 142 fell at or within one grid point of a combined value of 10 or greater. The remaining 43 fell in areas with combined values less than 10. It was obvious in examining many of these cases that the combined value could have reached 10 or greater and receded again during the time interval between data observation and tornado observation. There were other cases in which the reporting time of the tornado could be questioned. Table 2 summarizes the relationships discussed above.

7. SUMMARY

This is the first time vorticity acceleration has been related to a large number of tornado occurrences. It was felt that to try to show the relationship without a thermodynamic parameter would be as misleading as showing the relationship of tornadoes to air mass instability without a kinematic parameter. It is gratifying to see how combining the values of the two parameters eliminated from consideration large portions of both the unstable air mass and areas of positive vorticity acceleration. Tornadoes developed only when the two areas overlapped each other and then only when their combined value reached a critical figure. It is interesting to note that even in areas of large positive vorticity acceleration few tornadoes formed unless the stability index was —2 or less. Also, few tornadoes formed in very unstable air unless the vorticity acceleration was 0.02 or larger. These two parameters obviously play a very important role in the development of tornadoes. However, other parameters must be considered before the tornado environment can be definitely recognized.

Nothing has been said about the problem of forecasting the values of these parameters. This opens a whole new field of investigation. However, before any attempt is made to forecast these parameters, their relationship to tornado occurrences should be definitely established and properly evaluated. This has been the sole purpose of this study.

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